Determining the Higgs Properties Post-Discovery

Radja Boughezal

DOE Site Visit, September 4, 2012

Argonne NATIONAL LABORATORY

After the euphoria

- Two months ago today, the announcement of the Higgs discovery generated great excitement

- With the excitement over (or at least reduced), it's now time to analyze the discovery
- Is it the Standard Model Higgs, or do its couplings deviate?
- In fact, is it even a Higgs boson, or could it be something else (a spin-2 state, or a CP-odd scalar, or ...)?

Threshold behavior in $H \rightarrow 4l$

- Several ways to answer this, which we'll talk about
- We developed one which we believe has the advantage of simplicity, ease of application with the initial data, and ability to trivially combine ATLAS and CMS data
- In H -> ZZ -> 4l, with lepton-pair invariant masses M_{12} and M_{34}, the threshold behavior differs for various spin/CP combinations as M_{34} approaches its maximum M_H-M_{12}
- Developed in collaboration with our ATLAS colleagues upstairs

R. B., T. LeCompte, F. Petriello arXiv:1208.4311

Threshold behavior in H→4l

- Seve
- We ... f simplicity,

  ease ... ally combine

  ATL
- In H ... nd M_{34}, the

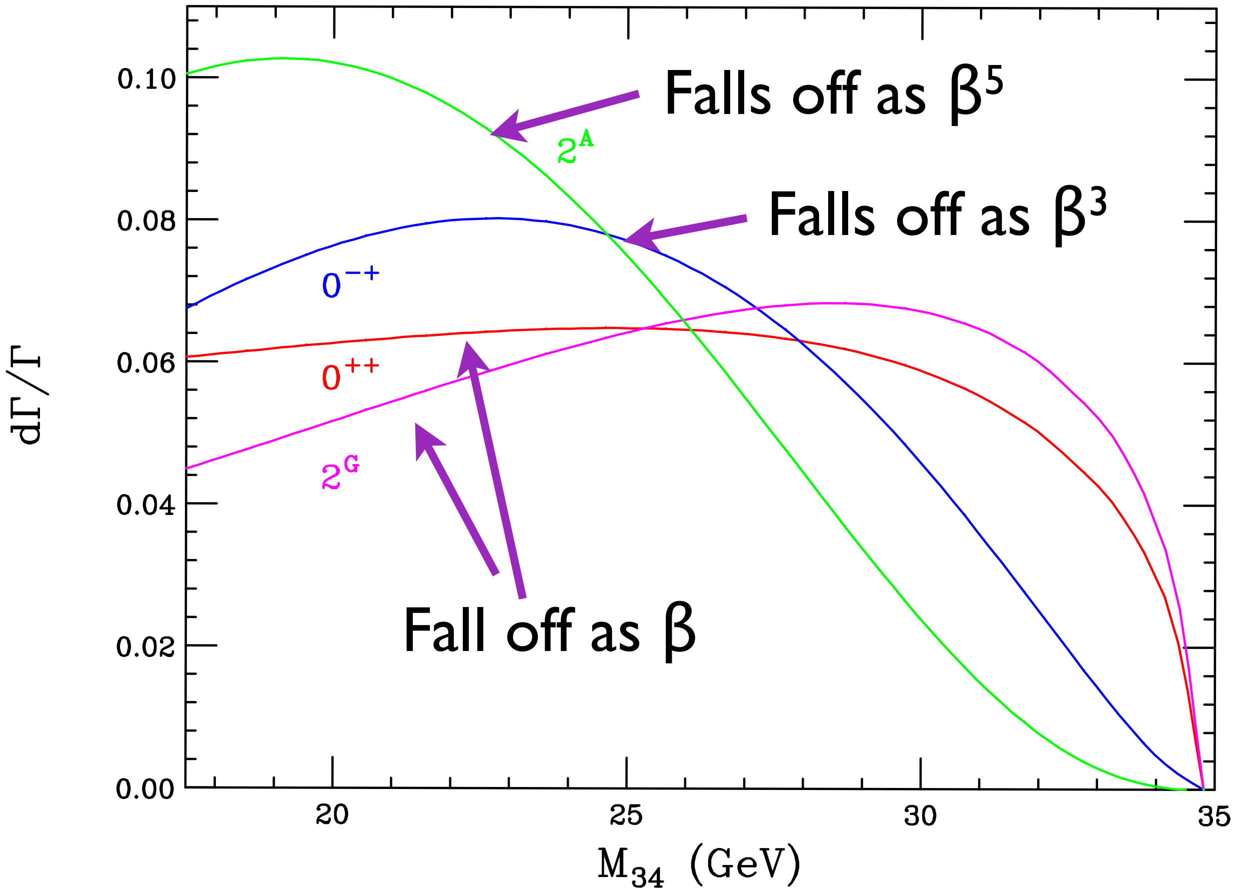
  thre ... ons as

  M_{34}
- Dev ... pstairs

R. B., T. LeCompte, F. Petriello arXiv:1208.4311

The M_{34} asymmetry

- Consider several example spin/CP combinations



β=momentum of 34 system in Higgs rest frame

- A simple asymmetry captures this difference in shape:

$$\mathcal{A}_{M_{cut}} = \frac{N(M_{34} > M_{cut}) - N(M_{34} < M_{cut})}{N(M_{34} > M_{cut}) + N(M_{34} < M_{cut})}$$

Results with one handful of events

- Consider an initial study of ATLAS+CMS events consistent with ZZ^* production. This is just 10 events, with half expected to be background! Note that the extension to Z^*Z^* is not difficult, not done here for simplicity of M_{cut} choice.

$$\mathcal{A}_{26}^{sig+back}(0^{++}) = -0.060, \quad \mathcal{A}_{26}^{sig+back}(2^A) = -0.31$$

A_{26}(data) = 0±0.28

⇒Already disfavor 2^A at the 1-σ level

$$\mathcal{A}_{28}^{sig+back}(0^{++}) = -0.31, \quad \mathcal{A}_{28}^{sig+back}(0^{-+}) = -0.44$$

A_{28}(data) = -0.40±0.27

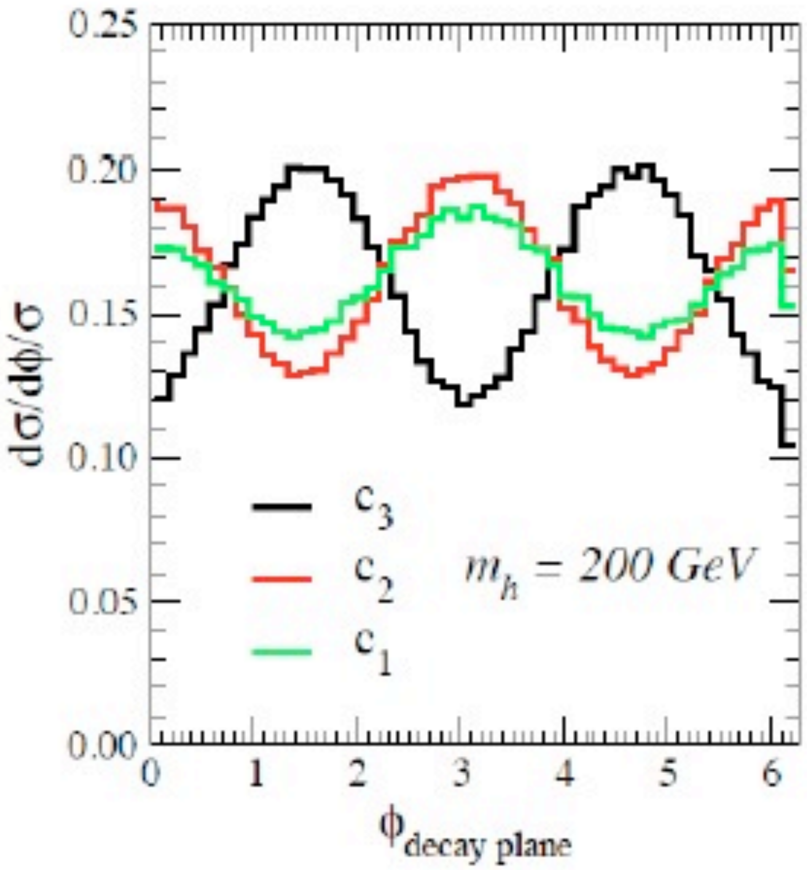
⇒data uncertainty too large right now, need more luminosity

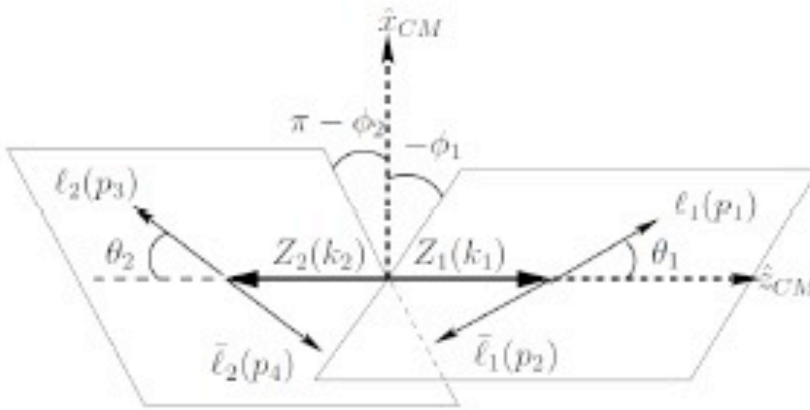
- Looking forward to continued fruitful collaboration with our ATLAS colleagues in pursuing this analysis arXiv:0911.3398 by Cao, Jackson, Keung, Low, and Shu

Testing the scalar couplings to ZZ:

$$\mathcal{L}_{eff} = \frac{1}{2} m_S\, S \left(c_1 Z^{\nu} Z_{\nu} + \frac{1}{2}\frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

higgs mechanism predicts only this term!

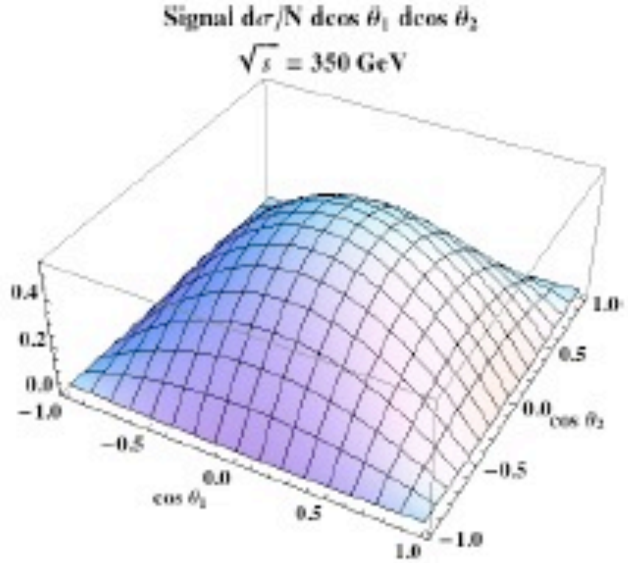




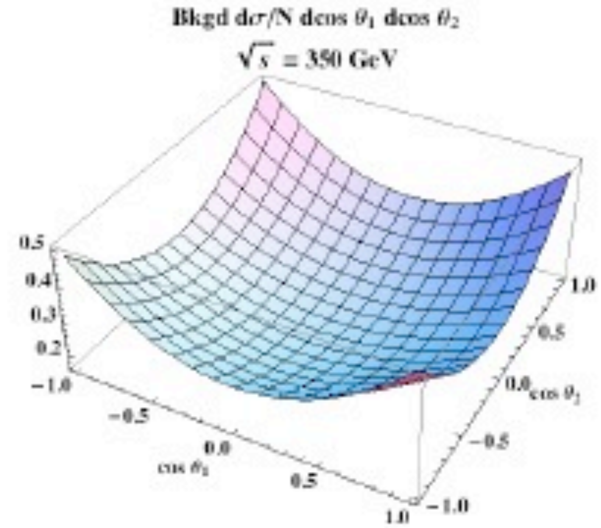
A simple observable: the azimuthal angle between the two decay planes:
~ cos($2\phi+2\delta$)
δ =0 --> CP-even scalar
$\delta = \pi/2$ --> CP-odd scalar
A general δ implies a mixture of CP-even and CP-odd states and hance CP-violation!

arXiv:1108.2274 by Gainer, Low, Kumar, and Vega-Morales

To test the spin and CP properties of the new resonance, one usually assumes a pure sample of signals. This could be avoided if the fully differential distributions of the background is known! (The background could mimic certain spin-2 distributions!)



CP-even scalar



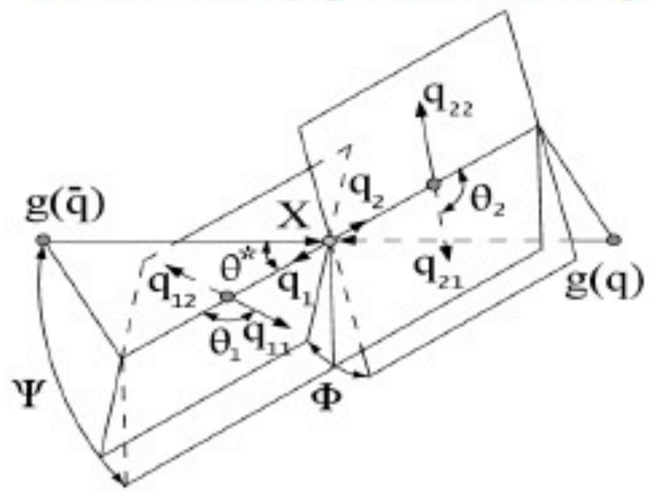
qqbar->ZZ bkgd

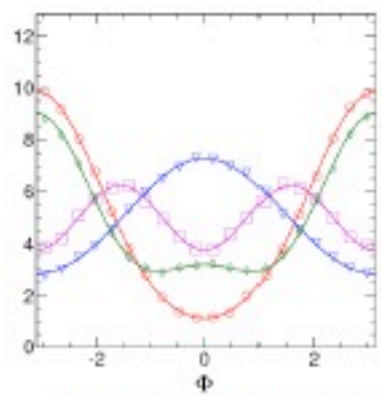
At 125 GeV the dominant bkgd is from qqbar->Z+Gamma*->4l, which wasn't available. This is the reason CMS only used 2d distributions in the discovery of the new resonance in the 4lepton channel, while they used 7d distributions in the high mass exclusion limits.
We have since computed this process and helped CMS implement it in their analysis.
The "Background" hypothesis should now be included in testing the spin and CP properties.

On the spin and parity of a single-produced resonance at the LHC

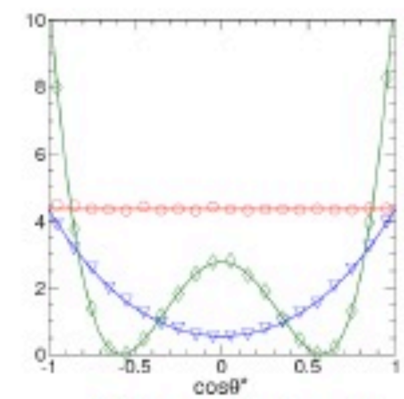
Discovery is just the beginning – we need to understand the properties

- We explore spin and parity quantum numbers through **angular analysis** of the decay products in pp → Higgs → *ZZ*, *WW*, $\gamma\gamma$.





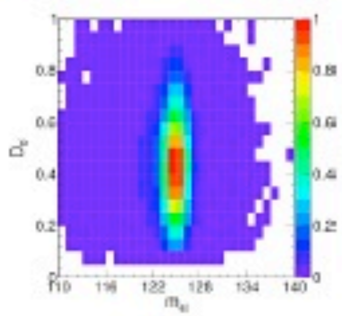
different spin 0 and 2 hypothessi in X→*WW*



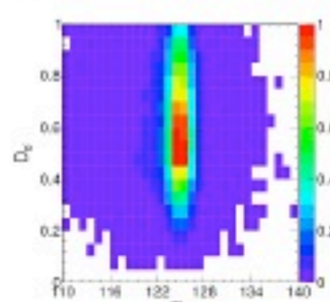
different spin 0 and 2 hypothessi in X→$\gamma\gamma$

- To enhance hypothesis separation we developed a multi-variate analysis (**MELA**)

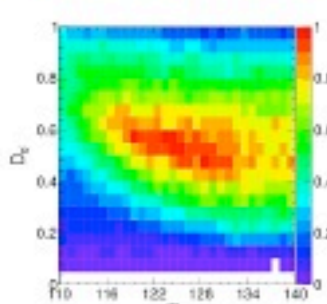
2-dim. analysis MELA vs. m_{4l}



SM Higgs



spin-0 pseudoscalar



SM background

On the spin and parity of a single-produced resonance at the LHC

Analysis tools:

- analytic results **and** publicly available event generator (*JHUGenerator*)
- general couplings of spin-0, spin-1 and spin-2 resonance
  to qqb, gg initial states and ZZ,WW,$\gamma\gamma$ final states
  including off-shell and interference effects
- include main backgrounds and detector simulation

Accomplishments:

Expected separation significance (Gaussian σ) for 35 fb^{-1} integrated luminosity at the 8 TeV LHC

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0^+_m vs background	7.1	4.5	5.2	9.9
0^+_m vs 0^-	4.1	1.1	0.0	4.2
0^+_m vs 2^+_m	1.6	2.5	2.5	3.9

- MELA framework was used in CMS Higgs discovery analysis (H→ZZ) to improve S/B ratio
- *JHUGenerator* is being used by more than 40 users for independent analyses